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## DISTRIBUTED OPTICAL FIBER SENSOR WITH CONTROLLED RESPONSE FIELD OF THE INVENTION

This invention relates to optical fiber sensors and more particularly to such sensors which include materials in the coatings and/or claddings of optical fibers which produce changes in the characteristics of the light carried by the fiber responsive to the presence of a material or field to be detected.

### BACKGROUND OF THE INVENTION

U.S. Patent No. 4,834,496 issued May 30, 1989 discloses distributed fiber optic chemical sensors. Such a sensor comprises an optical fiber with a core and a cladding which is permeable. The cladding, or a coating on the cladding, includes a composition, the optical properties of which are altered in the presence of a material to be detected. The light (i.e. the wavelength or the intensity of the light) transmitted through the core of the fiber is a function of the change in optical properties caused by the interaction of the composition included in the permeable coating with the material to be detected. The change in optical properties may comprise (for example) a change in the index of refraction (or indices of refraction differential), or an increase or decrease in the optical absorbance or fluorescence of the composition.

The above-noted patent discloses materials, compositions, sensing parameters and examples of such sensors, all of which are useful in accordance with the principles of this invention. In addition, distributed fiber optic sensors for physical properties, such as temperature or pressure, can also be fabricated based on similar properties, e.g., temperature-induced or pressure-induced changes in the refractive index, optical

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absorbance, or fluorescence of a cladding or coating material applied to a light-guiding core.

Unfortunately, such optical fibers are characterized by spatial transients for transmitted light which causes the sensitivity of chemically or physically sensitive fibers to vary from point to point along the fiber. This is particularly true of multi-mode fibers with lossy (e.g. absorber-doped) coatings where light does not reach equilibrium for a considerable distance. Such a varying response is due to a spatial transient, associated with the existence of radiation modes, and a stronger attenuation of higher order bound modes. Accordingly, sensor response over the length of the fiber is not constant.

#### BRIEF DESCRIPTION OF THE INVENTION

In accordance with the principles of this invention, the fraction of light lost per unit length may be controlled by controlling the physical design of the fiber. One use for this invention is to compensate for the spatial transient in distributed fiber optic sensors, wherein a constant sensitivity over the length of a distributed fiber sensor is achieved by introducing a change in the light-guiding characteristics of the fiber to compensate for the effects of spatial transients. Thus, for example, in one embodiment, a loss-compensated distributed optical fiber sensor comprises a core and a cladding where the core to cladding refractive index differential increases with length to compensate for the loss of higher order modes in the (multi-mode) fiber. As a result, a highly uniform, distributed sensor is realized.

#### BRIEF DESCRIPTION OF THE DRAWING

Fig. 1 is a schematic illustration of an optical fiber.

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Fig's. 2 is a graph of power transmitted vs. fiber position for prior art apparatus;

Fig. 3 is an illustrative embodiment in accordance with the principles of this invention; and

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Fig. 4 is a graph of refractive index variation with distance from the launch end of a fiber in accordance with the principles of this invention..

Fig. 5 is a plot of power transmitted vs. fiber position that results when light is launched into a fiber the refractive index of which varies as shown in Fig. 4.

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Fig. 6 is a block diagram of a system using the fiber of Fig's. 1 and 3.

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Fig. 7 is a block diagram of a further system using the fiber of Fig's. 1 and 3.

Fig. 8 is a plot of energy loss vs. fiber position that results when light is launched into the fiber of Fig. 5 when a section of the fiber is exposed to a target chemical substance.

Fig. 9 is a plot of chemical concentration vs. fiber position that can be derived from Fig. 8.

#### DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS OF THE INVENTION

Multi-mode absorption based distributed sensors have an output response given by

$$P \approx P_0 \frac{V}{al} \quad (1)$$

as is well known. In the equation, V is the fiber number given by

$$V = ka \sqrt{n_{co}^2 - n_{cla}^2}, \quad (2)$$

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where  $P_0$  is the power at the input end of the fiber,  $P$  is the power at a distance  $l$  from the input end,  $a$  is the core radius,  $\alpha$  is the absorption coefficient of the cladding, and  $n_{co}$  and  $n_{cla}$  are the core and cladding refractive indices. Equation (1) is the generic response, which can be observed as a change in total transmitted light intensity using a simple detection scheme, observed as a plot of backscattered power versus length in an optical time domain reflectometer (OTDR), of a multi-mode optical fiber with an absorbing cladding. It is clear that the power lost per unit length at each position along a distributed optical fiber sensor is different from the power lost per unit length at any other position along the fiber.

Fig. 1 shows a representative distributed optical fiber sensor. The power can be calculated for each of the positions from the input (di) to the output (do) and at any of the positions  $d_2, d_3, d_4, d_5, d_6 \dots$  in between. Accordingly, the power along the length of the fiber is given by:

$$P = P_0 \exp \left( -\sum_{i=1}^N \int_0^l \alpha(z) \eta_i(z) dz \right) \quad (3)$$

In accordance with the present invention, a distributed, multi-mode optical fiber sensor can be made to exhibit a linear response in the dB scale. A linear response to changes in absorption may be achieved by compensating for the absorption fall off of Fig. 2 by:

- a) increasing the core/cladding refractive index ratio along the fiber length
  - b) increasing the core diameter along the fiber length
  - c) increasing the absorption coefficient of the sensor material in the cladding along the fiber length
  - d) increasing the absorption coefficient of the cladding along the fiber length
  - e) increasing the scattering coefficient of the core along the fiber length
  - f) varying the parameters (a,b & c) together or in varying combinations

Fig. 2 is a plot of power radiated per unit length versus fiber length  $l$  for a typical multimode fiber. The absorption coefficient clearly falls off. The absorption coefficient change is due to the fact that all modes in an optical fiber are attenuated differently. Modes closer to cut off (i.e., modes that have an angle of incidence in the core/cladding boundary closer to 90 degrees) are attenuated quicker than modes far from cut off. In order to obtain an even attenuation as a function of length, coupling from lower order modes to higher order modes must occur. Even attenuation is achieved, for example, by increasing the core diameter as shown in Fig. 3 or by varying the core/cladding refractive index ratio or by increasing the absorption coefficient or scattering coefficient along the length of the fiber to compensate for the lower attenuation rate of modes that are increasingly far from cut off.

Fig. 4 is a plot of  $N_{co}/N_{cla}$  versus fiber length for a multi-mode, distributed sensor optical fiber in accordance with the principles of this invention. It is clear that an optical fiber so designed exhibits a power loss which is linear over the length of the fiber, for the combined effect of the spatial transient of Fig. 2 and the length-variation of fiber physical

parameters (e.g., the refractive index, as shown in Fig. 4) is to linearize the power versus length curve (Fig. 5), thus creating a fiber sensor the sensitivity of which does not vary as a function of length.

Fig. 6 is a block diagram of sensor apparatus employing a fiber optic sensor of the type shown in Fig. 4. The fiber 100 includes a core 125 transmissive of electromagnetic radiation (e.g. light) and a cladding or sheath 126 of a permeable material. The index of refraction of sheath 126 is lower than that of core 125, and may vary with length. The fiber may include a coating 127 which also would be of a permeable material.

A reactant to be detected, causes a change of, for example, the intensity of light back scattered toward the end into which light is launched. The input light is launched, and the output light is detected by detector 131 as noted herein before.

Light energy is introduced at the input end of the fiber by, illustratively, a laser 132 and the properties of the light energy (e.g. intensity, wavelength - - -) are modified by interaction between material in the fiber sheath and the reactant to generate backscattered light characteristic of the reactant and the interaction with the sheath material.

The importance of structuring the fiber so that this interaction is constant over the length of the fiber is most clear in applications where the presence of a test chemical (reactant) may be at any point along the fiber and a cumulative effect over the length of the fiber is not an issue. The use of an ODTR, as shown in Fig. 7, permits the position of the reactant along the fiber to be determined as indicated in Fig's. 8 and 9. In addition, such a loss-compensated sensor fiber can be used to accurately measure average chemical concentration over the entire fiber length by measuring the total light loss induced by the presence of the chemical using the system of Fig. 6. This is not possible for fibers the

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power versus length curve of which is nonlinear (e.g. Fig. 2). An optical fiber structured in accordance with this invention to exhibit a length-invariant response to such interactions is also advantageous for illumination applications and for applications in which an accumulated response is desired as in U.S. Patent No. 4,321,057 issued March 23, 1982 and in the above noted patent No. 4,834,496 where the portion of the length of fiber affected may be compared to some threshold for triggering an alarm.

An optical fiber having a core of F-2 Schott glass with a diameter of 100 micrometers and a cladding of polymer with a thickness of 20 micrometers was fabricated and a twenty meter length of the fiber was tested at 850 nm (active wavelength) as a moisture sensor. A reference wavelength of 1300 nm also was used. A dry reference measurement was made and then increasing lengths of 10 cm, 20 cm, and 50 cm were wetted. A final reading was taken after allowing the 50 cm wet length to air dry for one hour. At 1300 nm only a slight change (< 1 dB) in output intensity occurs after an input signal propagates more than 10 meters along the fiber. A significant change of 2.4 dB is detected at 850 nm. The OTDR was able to determine the location of the moisture site to within 1 cm using 850 nm light and the 1300 nm light was capable of being used to compensate for transmission charges due to effects other than moisture.

A PH- sensitive fiber was also tested, in a manner similar to that for the moisture-sensitive fiber, immersed in PH-7 and PH-10 buffer solutions. At 1300 nm there was virtually no change in output intensity. At 850 nm a substantial change of 1.2 dB occurred. The OTDR was able to locate the position of the buffer solution along the fiber to within 2 cms at 850 nm, and again the 1300 nm signal could be used as a "reference".

The ability to structure a fiber to control the fraction of light lost per unit length in accordance with the principles of this invention also permits a fiber to be constructed to provide an arbitrary power loss profile along the fiber. By so doing, a fiber sensor may be provided which is particularly sensitive at a predesignated position in the fiber.

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